Estimation of the Dynamic Pressure around a Fully Loaded Blasthole

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ABSTRACT:

In the studies of the rock response adjacent to a blasthole, the dynamic pressure generated by explosive detonation needs to be either measured, which is costly and difficult, or calculated theoretically, which is also complicated. For research engineers, a simple empirical formula is often preferred to obtain quick and reasonably accurate estimations. This paper describes a semi-empirical method for such an approach. The format of the formulas is empirical, however the data based on which the equations are derived are from theoretical (hydrodynamic) modelling. In this semi-empirical approach, the properties of both the explosives and the rock are considered for calculating the peak borehole pressure and the pressure decay around a fully loaded blasthole. Experimental results, obtained in granodiorite rock, are used to calibrate one of the constants in the estimation of pressure decay. With the estimated pressure in the rock, it is possible to predict the pressure in a different media, such as water, where a measurement device can be imbedded. The calculation of stress wave reflection at the boundary is also described in this report.

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Estimation de la Pression Dynamique autour d'un Trou Chargé

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RÉSUMÉ

L'étude de la reaction de la roche qui se trouve adjacent à un trou de forage, démontrent que la pression dynamique créée par l'explosion doit être mesurée ou calculée. Ceci s'accompagne de plusieurs problèmes: c'est difficile, coûteux ou c'est très compliqué. Les ingénieurs preferrent utilisé une formule simple et empirique, qui leur donnerait une estimation qui est raisonnablement precise. Ce papier décrit une méthode semi-empirique qui a comme but de simplifier les calculs nécessaires. Le format de la for-mule est empirique mais tous les donnés et les equations utiliser sont dérivés d'un modèle hydrodynamique théorique. Dans cette estimation semi-empirique, en calculant la pression maximum et son niveau de désintégration, toutes les propriétés des explosifs et de la roche sont consider&s. Les résultats expérimentaux obtenus pour des roches granodiorite sont utilisés pour calibrer un des constant pour l'estimation de le niveau de désintégration de pression. Avec les estimés de la pression obtenus dans la roche, il est possible de prévoir comment d'autres sortes de mediums seront affectées par des explosions similaires. Dans ce cas ci le médium inconnue est un fluide ou une mixture gelatineuse qui entoure et protege l'appareil de mesurement. Le calcule de la reflection d'onde du choque a la **frontiére** est **décris** aussi **dans** ce rapport.

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INTRODUCTION

One of the fundamental aspects in the study of the rock-explosives interaction after detonation is to determine the dynamic pressure generated around a blasthole. The knowledge of dynamic pressure is useful for other studies such as the explosives behaviour under dynamic precompression and the rock breakage and damage mechanisms.

The measurement of the dynamic pressure around a blasthole is usually costly and difficult to achieve because of the extremely high pressure and temperature. Conversely, if a computer simulation package is used, the procedures are often quite complicated. For field engineers, such experimental or computing facilities are rarely available. Thus a format of simple empirical equations is most welcome to serve as a useful tool to estimate the magnitude of such dynamic pressures. The first empirical equation of this type for rocks was developed by Hino [1] as follows:

$$P=P_m\left(\frac{R}{R_0}\right)^{\alpha} \qquad (1)$$

where P is the pressure at distance R from the centre of a blasthole;

P_m is the maximum pressure at the blasthole wall;

R_0 is the blasthole radius.

α is the pressure decay, α =-1.5 for rocks in general.

The maximum pressure P_m was treated as the detonation pressure of the Chapman-Jouguet.

(C-J) state:

$$P_d = \frac{10}{1+\gamma} \rho_0 D^2 \qquad (2)$$

where ρ_0 is the density of explosives, in g/cm^3;

D is the velocity of detonation of explosives, in km/s;

y is the ratio of the specific heats of the detonation gases, which is simplified as follows:

$$\begin{aligned} y &= 2.1 \quad \text{for } p \leq 1.2 \ g/cm^3; \\ y &= 3.0 \quad \text{for } p > 1.2 \ g/cm^3 \end{aligned} \qquad (3)$$

The discontinuity in Equation (3) is inconvenient and a crude approximation. A more scientific expression was given by Defourneaux [2] to link the y with the density of CHNO (carbon, hydrogen, nitrogen and oxygen) type of explosives:

$$\gamma = 1.9 + 0.6 \times \rho_0 \qquad (4)$$

Using Equations (1), (2) and (4), one can obtain the dynamic pressure in kbar if ρ_0 is in g/cm^3 and D in km/s.

As expressed in Equation (1), the two parameters determining the pressure magnitude are the borehole pressure P_d (when $R/R_0=1$) and the pressure decay, α. With Hino's assumption that $\alpha=-1.5$ and P_d equal to the detonation pressure, this estimation was found to be suitable for hard rocks such as granite [1]. However, it must be pointed out that the detonation pressure is not necessarily the borehole pressure seen by the wall of in the rock. Furthermore , this equation does not reflect the influence of the properties of explosives and rocks. Therefore its use is limited when various types of explosives and rocks are combined.

To overcome the drawbacks of Hino's method, both the borehole pressure and the pressure decay must be correlated with the properties of explosives and rocks. Liu and Katsabanis [3] developed a hydrodynamic method to calculate the dynamic pressures around a blasthole, which was aimed to estimate the crushed zone around a blasthole. Like other computer modelling, the properties of both explosives and rocks were considered. However one must work out a computer program to carry out the calculations, which is often tedious and difficult since it requires a full understanding of detonation physics and hydrodynamics.

The rock dynamic pressures in the modelling were calculated by considering a detonation wave propagating along a cylindrical explosives charge in rock. When the rock wall is shocked by the detonation front, a shock wave is produced in the rock and propagates outwards. As an approximation, cylindrical wave properties were evaluated at the explosive-rock interface. The shocked rock has an increase in density. The density change in turn causes an isentropic expansion of the detonation gases. In this geometry, the pressure in rocks is always smaller than the detonation pressure.

For the attenuation of the dynamic pressure around a blasthole, the model assumes that the shock wave is supported by the expansion of the blasthole diameter before the detonation gases are released. Between the shock front and the borehole wall, the density behind the shock wave is assumed not to change (Zhang, [4]). This assumption is obviously limited to the region not too far away from the blasthole. Therefore the applicable distance range of this model has been under investigation during the past few years, until experimental results were available to confirm the calculations.

SEMI-EMPIRICAL EQUATIONS

Liu and Katsabanis [3] performed regression analysis on the modelling results for a variety of explosives and rock combinations in order to determine P_m and α while still using the same general format of pressure attenuation as Equation (1). P_m and α were summarized by the following equations and the constants were obtained by multiple linear regression.

$$P_m = a_1 (\rho_o D^2) \left(\frac{\rho_r}{\rho_o}\right)^{b_1} \left(\frac{C}{D}\right)^{c_1} \quad (5)$$

$$\alpha = a_2 \left(\frac{P_H}{\rho_o}\right)^{b_2} \left(\frac{C}{D}\right)^{c_2} \quad (6)$$

where P_m is the maximum dynamic pressure on the borehole wall, kbar;

α is the pressure decay factor;

D is the VOD of the explosive, km/s;

C is the sound velocity in rock, km/s;

ρ_o and ρ_r are the density of explosive and rock respectively, g/cm^3;

a_1, bI, c_1 and a,, b_2, c_2 were determined by multiple linear regression. The following Table gives the obtained values and 95 % significance deviation obtained from the calculation of 4 types of explosives detonated in 9 types of solid materials [3]

Table 1. Regression Parameters Based on the Data Generated by Numerical Modelling

For P_m:	a_1=1.635 ±0.095	For α:	a,=-1,471 ±0.034
	b_1=0.2388 f0.0523		b_2=-0.0809 ±0.0141
	c_1=0.2521 ±0.0507		c_2=-0.2756 ±0.0137

Although Equations (1), (5) and (6) are much easier to use than the complicated computation process, their format was purely based on regression results for non-dimensional factors. Furthermore, the physical meaning of these factors are not clear. Based on the fact that b_1, c_1 are quite similar in value, one constant can be assumed to replace the two. Then, the ratio powered by this constant, $(\rho_r C/\rho_o D)$, becomes the impedance ratio of rock over the explosives. Furthermore, b_2 is neglected because the correlation coefficient of (ρ_r/ρ_o) with α (0.81) is smaller than that (0.98) of (C/D), which is also implicated by comparing the absolute values of b_2 and c_2. In other words, the decay factor α has a strong correlation with (C/D) but very weak with (ρ_r/ρ_o). By neglecting b_2, α becomes a function of ratio C/D only. The error introduced by this is less than 8% considering the commonly encountered densities of rocks and explosives. The simplified equations are derived as follows:

$$P_m = a_1 (\rho_o D^2) \left(\frac{\rho_r \times C}{\rho_o \times D} \right)^{b_1} \qquad (7)$$

$$a = a_2 \left(\frac{C}{D} \right)^{b_2} \qquad (8)$$

From multiple linear regression on the same numerical modelling results, the constants are redetermined with the 95% significance deviation:

$a_1 = 1.62 \pm 0.04$;

$b_1 = 0.25 \pm 0.02$;

$a_{,,} = -1.35$ f0.03;

$b_2 = -0.33 \pm 0.01$.

By applying these constants to Equations (7) and (8), the simplified equations become:

$$P_m = 1.62\,(\rho_o D^2)\left(\frac{\rho_r \times C}{\rho_o \times D}\right)^{0.25} \tag{9}$$

$$\alpha = -1.35.\left(\frac{C}{D}\right)^{-0.33} \tag{10}$$

Again, P_m is in kbar if ρ_r and ρ_0 are in g/cm^3 and C and D are in km/s.

Equation (9) indicates that the P_m is proportional to the detonation pressure, moreover, it is a function of the so called acoustic impedance ratio of rock over explosives: $\rho_r C/\rho_0 D$. The pressure decay factor α is a function of the velocity ratio of the sonic velocity of rock over the VOD of explosives: C/D.

These semi-empirical equations are simple and easy to apply, The density and VOD of an explosive are usually specified by the manufacturer. The rock density can be easily measured and the sonic velocity can be treated as the P-wave velocity which can be determined experimentally or can be found in handbooks such as the CRC Practical Handbook of Physical Properties of Rocks and Minerals [5]

As mentioned earlier, the constants in these equations are obtained purely from the numerical modelling. For maximum pressure on the borehole wall, P_m, the calculation is believed to be fairly accurate because the calculation procedure follows well established hydrodynamics theory. In addition, calculation results for military explosives detonating in metals agreed very well with experimental results (Zhang, et al. [6]). The decay factor α, however, is based on the assumption that the shocked density of the rock remains unchanged between the shock front and the expanding borehole wall. In reality, the shock front travels, radially outwards from the wall even if the wall stops expanding. Thus, this

assumption applies mainly to the region close to the borehole wall. The pressure decay tends to be slower than the reality over a wider range of distances. Therefore, the constants in Equation (10) need to be modified according to experimental results.

EXPERIMENTAL MEASUREMENTS IN ROCKS

The measurement of dynamic pressures around blastholes was conducted at the CANMET/MRL Experimental Mine, in collaboration with the Group Technology Centre of ICI Explosives (Liu, Tidman, et al, [7]). Each experiment consisted of a central donor hole and two measurement holes on opposite sides. The spacings were varied from 196 mm to 406 mm. All the holes had the same depth (1.8 m) and diameter (32 mm) and were drilled downwards at about 10" in order to keep water inside for better coupling and more accurate measurement. The central donor holes were fully charged with an emulsion explosive which had an average VOD of 4350 m/s, as measured by a continuous VOD monitoring system.

Carbon resistors, as a pressure gauge device, were placed close to the bottom (about 50 mm) of the measurement holes. It is well-known that carbon composition resistors exhibit a linear change in resistance with pressure (Watson, [S]). In a half-bridge circuit, the change in resistance of the gauge resistor can be derived from the voltage signals which were recorded and stored on a digital oscilloscope. The oscilloscope was triggered by the VOD probe so it- is.. possible to determine the pressure pulse times in relation to the time of the donor charge initiation.

A shock wave travelling from one medium to another may only transmit part of the incident energy (Kolsky, [9]). The amount of energy transmitted is determined by the acoustic impedance of the two media. The acoustic impedance, Z, is defined as the product of density and sound velocity. The pressure gages were inserted in water-filled receptor holes. Since water has little compressibility, pressure measurements are usually reliable and the shock transmission from rock to water can be accounted for. In addition, little attenuation is expected when waves travel through water from the acceptor walls to the pressure gauge. Thus the peak pressure measured at the hole centre is assumed to be the same as the water-rock boundary at the receptor wall. The impedance values of water and the granodiorite host rock are listed as follows (Liu, Tidman, et al, [7]):

Granodiorite: C=5.6 km/s, ρ_r=**2.72** g/cc, Z_r=**15.23** km.g/s/cc;

Water: c=1.4 km/s, ρ_w=**1.00** g/cc, Z_w=**1.41** km.g/s/cc.

Based on wave reflections, the pressure reduction from the incident wave in rock to the transmitted wave in water is expressed by the following equations (Kolsky, [9]):

$$T = 2\frac{k}{1+k} \tag{11}$$

$$k = \frac{Z_w}{Z_r} \tag{12}$$

where T is the transmission factor.

k is the impedance ratio of water (w) over rock (r),

Z_w and Z_r are the impedances of water and rock respectively.

For stress waves travelling from the granodiorite to water, the transmission factor T is 0.1695.

The measured dynamic pressures in water are summarized in Table 2. The spacings at which the pressures were measured are also expressed in relative distance, $\mathbf{R/R_0}$. The calculated values for the incident wave in rock are based on Equations (11) and (12). The peak pressures in rock have been fit by a power law with the following form by regression:

$$P = 32.4 \left(\frac{R}{R_0}\right)^{-1.29} \qquad (13)$$

with standard error 6.5%.

By applying the properties of the explosives (ρ_0=1. 18 $\mathbf{g/cm^3}$ and D=4.3 km/s) and that of the granodiorite rock (ρ_r=2,72 $\mathbf{g/cm^3}$ and C=5.6 km/s) to Equations (9) and (10), the borehole pressure and the pressure decay are determined:

$$P_m = 1.62\,(\rho_o D^2)\left(\frac{\rho_r \times C}{\rho_o \times D}\right)^{0.25}$$
$$= 1.62\,(1.18\times 4.3^2)\left(\frac{2.72\times 5.6}{1.18\times 4.3}\right)^{0.25} = \mathbf{46\ \ 5\ \ kbar} \qquad (14)$$

As discussed earlier, the estimation of α, Equation (10), needs to be modified to comply with the experimental results. With P_m=46.5 kbar, the best fit to the experimental data yielded that α=-1.41. While keeping the same format of Equation (8) and the same power (0.33) of the variable (C/D) in Equation (10), one can obtain the constant a,:

$$-1.41 = a_2 \left(\frac{5.6}{4.3}\right)^{-0.33}; \quad a_2 = -1.54. \qquad (15)$$

Thus, Equation (10) is modified as:

$$a = -1.54 \left(\frac{C}{D}\right)^{-0.33} \qquad (16)$$

In summary, the semi-empirical approach yields the following equation for the experimental results with known rock and explosives properties:

$$P = 46.5 \left(\frac{R}{R_0}\right)^{-1.41}, \quad kbar \qquad (17)$$

with standard error 6.1%.

Table 2 gives the dynamic pressures from experimental measurement together with those from regression and the semi-empirical equations. The comparison of these results is also graphically shown in Figure 1.

Using an emulsion and **ANFO** explosives as an example, the P_m and α values are calculated, based on Equations (9) and (16), for some commonly encountered rock types and the results are tabulated in Table 3. The purpose of this exercise is to provide research engineers with some typical values to estimate the magnitude of the dynamic pressures around a blasthole in the studies such as rock fracturing and explosives malfunctioning.

Table 2. Dynamic pressures around a blasthole: Comparison of experiment results with semi-empirical estimations

Test #	Spacing (mm)	Relative distance (R/R_0)	Pressures from experiment, bar			Semi-empirical
			In water	In rock	Regression in rock (Eq. 14)	In rock, bar (Eq. 17)
P2	305	19.06	83	489.7	723	728
P5-1	197	12.31	230	1357.0	1270	1349
P5-2	298	18.63	136	802.4	745	753
P7-1	254	15.88	160	944.0	915	943
P7-2	406	25.38	121	713.0	500	487
P8-1	394	24.63	101	595.9	520	508
P8-2	241	15.06	154	908.6	980	1015
P9	311	19.44	102	601.8	705	709
P10	210	13.13	179	1056.1	1170	1233
P12	254	15.88	202	1191.8	915	943
P13	305	19.06	155	914.5	723	728
P14	311	19.44	68	401.2	705	709
P15-1	260	16.25	124	731.6	888	912
P15-2	210	13.13	278	1640.2	1170	1233

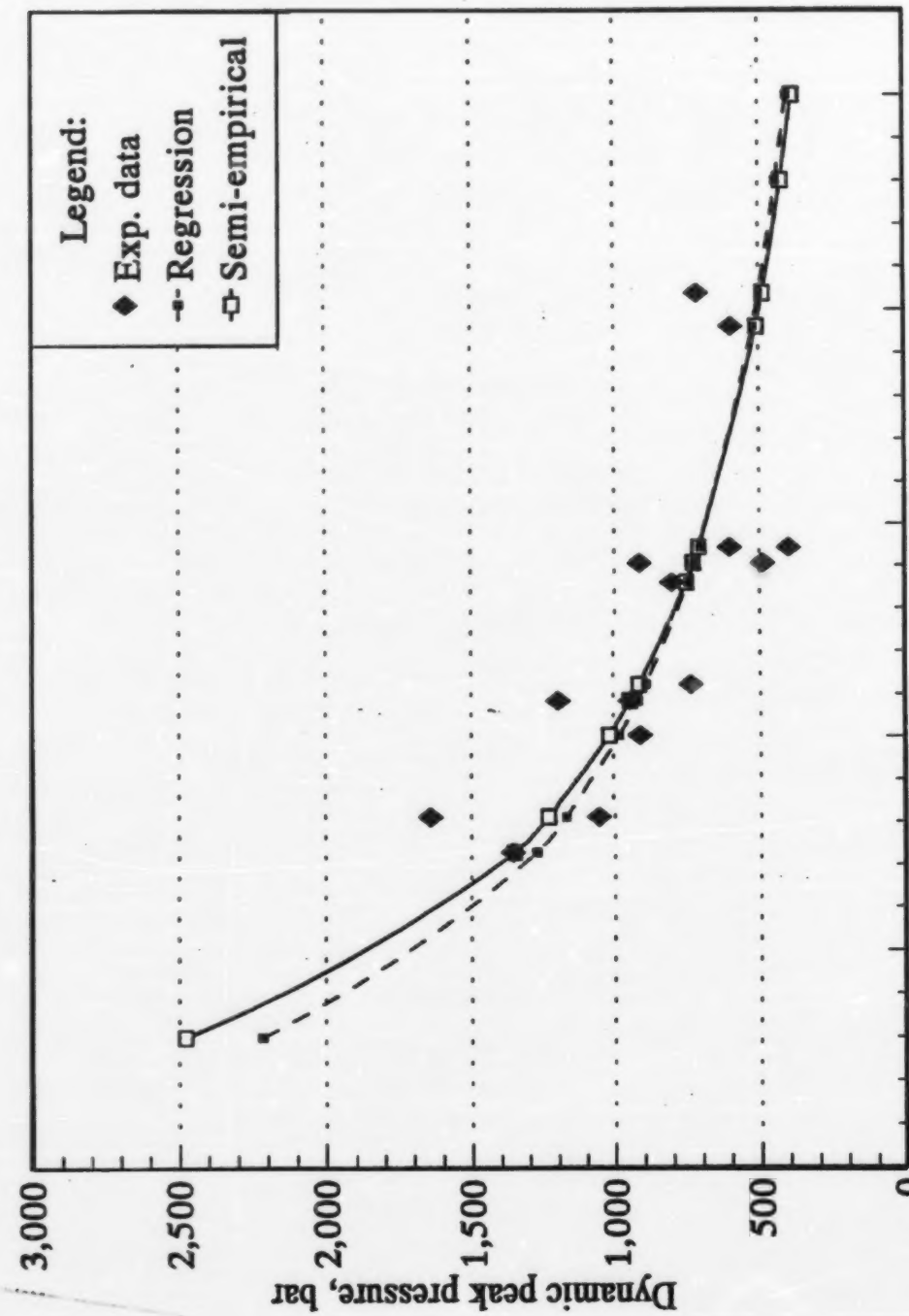

Figure 1. Dynamic pressure attenuation around a fully loaded blasthole: Comparison of experimental data with calculations.

Table 3. P_m and α values for some typical explosives and rock combinations

Rocks	Emulsion explosive ρ_0=1.18 g/cm³, D=4.3 km/s		ANFO: ρ_0=0.90 g/cm³, D=3.5 km/s	
	P_m, kbar	α	P_m, kbar	α
Limestone: ρ_r=2.6 g/cm³, c=3.5 km/s.	40.90	-1.65	23.29	-1.54
Granite: ρ_r=2.65 g/cm³, C=4.82 km/s.	44.52	-1.48	25.34	-1.39
Granodiorite: ρ_r=2.72 g/cm³, C=5.6 km/s.	46.52	-1.24	26.49	-1.32
Pyrite: ρ_r=5.0 g/cm³, C=6.0 km/s.	55.12	-1.38	31.38	-1.29

CONCLUSIONS

The semi-empirical equations developed in this report are based on both theoretical calculations and experimental measurements. The equations are summarized as follows for estimating the magnitude of dynamic pressures around a fully loaded blasthole:

$$P=P_m\left(\frac{R}{R_0}\right)^a \qquad (18)$$

$$P_m=1.62\,(\rho_o D^2)\left(\frac{\rho_r \times C}{\rho_o \times D}\right)^{0.25} \qquad (19)$$

$$a=-1.54\left(\frac{C}{D}\right)^{-0.33} \qquad (20)$$

The applicable distance of this estimation method, as observed so far: R/R,-,< 30, is within typical distances where explosives malfunctions are observed and some typical spacings or burdens which are used in development blasts. The validity of this method for greater distances needs to be confirmed or modified with additional experiments.

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